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Explicit CP violation in the MSSM through $gg \rightarrow H_1 \rightarrow \gamma\gamma$

S. Hesselbach[a1], S. Moretti[b2], S. Munir[c3], P. Poulose[d4]

[a] *IPPP, University of Durham, Durham, DH1 3LE, UK*
[b] *School of Physics & Astronomy,*
University of Southampton, Highfield, Southampton SO17 1BJ, UK
[c] *Instituto de Física, Departmento de Física Teórica,*
Universidad Nacional Autónoma de México, Apartado Postal 20-364,
01000, México, D.F.
[d] *Physics Department, IIT Guwahati, Assam 781039, INDIA*

Abstract

We prove the extreme sensitivity of the $gg \rightarrow H_1 \rightarrow \gamma\gamma$ cross section at the Large Hadron Collider on the explicitly CP-violating phases of the Minimal Supersymmetric Standard Model, where H_1 is the lightest Supersymmetric Higgs boson.

1 Introduction

One of the main reasons to build the Large Hadron Collider (LHC) at CERN is the determination of the mechanism of Electro-Weak Symmetry Breaking (EWSB). In the Standard Model (SM) of elementary particle physics and its extensions incorporating Supersymmetry (SUSY), EWSB occurs through the Higgs mechanism, which in turn leads to the existence of one or more Higgs particles.

Within the Minimal Supersymmetric Standard Model (MSSM), a realisation of SUSY with minimal particle content and gauge structure, the Higgs potential conserves Charge & Parity (CP) at tree level [1]. Beyond the latter, several studies have shown that CP invariance of the Higgs potential may in principle be broken by radiative corrections [2], as

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[1]stefan.hesselbach@durham.ac.uk
[2]stefano@soton.ac.uk
[3]smunir@fisica.unam.mx
[4]poulose@iitg.ernet.in

the Vacuum Expectation Values (VEVs) of the two Higgs doublets can develop a relative phase [3]. This type of CP violation is generally referred to as spontaneous CP violation and it requires a light Higgs state as a result of the Georgi-Pais theorem [4], but the possibility of the latter has now been essentially ruled out by experiment [5].

CP violation can also be explicitly induced in the MSSM, in much the same way as it is done in the SM, by complex Yukawa couplings of the Higgs bosons to (s)fermions. There are several new parameters in the SUSY theory, that are absent in the SM, which could well be complex and thus possess CP-violating phases.

However, the CP-violating phases associated with the sfermions of the first and, to a lesser extent, second generations are severely constrained by bounds on the Electric Dipole Moments (EDMs) of the electron, neutron and muon. Nonetheless, there have been several suggestions [6]–[8] to evade these constraints without suppressing the CP-violating phases.

By building on the results of Refs. [9, 10] (for the production) and [11]–[14] (for the decay) – see also Refs. [15]–[18] – we will look here at the LHC phenomenology of the $gg \to H_1 \to \gamma\gamma$ process (where H_1 labels the lightest neutral Higgs state of the CP-violating MSSM), which involves the (leading) direct effects of CP violation through couplings of the H_i ($i = 1, 2, 3$ corresponding to the three neutral Higgs bosons) to sparticles in the loops as well as the (subleading) indirect effects through scalar-pseudoscalar mixing yielding the CP-mixed state H_i. All sources of CP-violation are reviewed in the next Section, where we also lay down our nomenclature and conventions. In the following Section we present our results, then we conclude.

2 CP violation in the di-photon Higgs search channel

Explicit CP violation arises in the Higgs sector when various related couplings become complex. One consequence is that the physical Higgs bosons are no more CP eigenstates, but a mixture of them [19]. One may look at the production and decay of the lightest of the physical Higgs particles, hereafter labelled H_1. CP-violating effects in the combined production and decay process enter through:

1. Complex H_i-$\tilde{f}$-$\tilde{f}^*$ couplings at production level.

2. Complex H_1-$\tilde{f}$-$\tilde{f}^*$ couplings at decay level.

3. Mixing in the propagator.

The leading contribution to Higgs production in gluon fusion is at the one loop level. Similarly the leading contribution to di-photon decay channel is also at one loop level. These loops contain besides SM particles also Supersymmetric particles ($\tilde{\chi}^\pm$, $\tilde{t}_{1,2}$, $\tilde{b}_{1,2}$, $\tilde{\tau}_{1,2}$) where the phases of the SUSY parameters enter.

In earlier works we studied CP violation effects in the di-photon decay channel [11]–[14]. Presently we also consider the effect coming from its production as well as its propagation. The effect in the production is very similar to that of the decay [11]–[14]. Like in the latter case, we expect a strong impact of a light stop quark in some regions of the parameter

space. The propagator is considered in the following way. A Higgs particle, H_i, produced through gluon fusion, can be converted into another mass eigenstate, H_j, through interaction of fermion or gauge boson loops (see Fig. 1). In the following, when talking about results for the H_1, we consider the production of any of H_i, $i = 1, 2, 3$, which, while propagating, converts into H_1. This H_1 decays then through the di-photon channel. The propagator
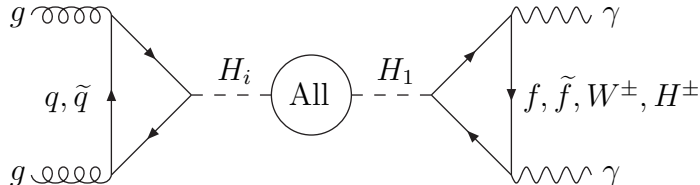

Figure 1: Leading order Feynman diagram for $gg \rightarrow H_1 \rightarrow \gamma\gamma$ including the effect of mixing in the propagator.

matrix is obtained from the self-energy of the Higgs particles computed at one-loop level, where we used the expressions provided by [20] which include off-diagonal absorptive parts. The matrix inversion required is done numerically using the Lapack [21] package. All relevant couplings and masses are obtained from CPSuperH version 2 [22], which takes into account all applicable experimental constraints including the low energy EDMs. The cross section of the full process shown in Fig. 1 is computed numerically. The multi-dimensional integration is carried out using the CUHRE program under the CUBA package [24]. For our collider analysis we have used the CTEQ6 Parton Distribution Functions (PDFs) [23].

3 Results

In order to illustrate the typical effects of CP-violation in the MSSM, we have considered a few sample parameter space points and studied the effect of CP violation, in particular the significance of light sparticles in the loops.

We fix the following MSSM parameters which do not play a role in CP violation studies:

$$M_1 = 100 \text{ GeV}, \quad M_2 = M_3 = 1 \text{ TeV}, \quad M_{Q_3} = M_{D_3} = M_{L_3} = M_{E_3} = M_{\text{SUSY}} = 1 \text{ TeV}.$$

We consider the case of all the third generation trilinear couplings being unified into one single quantity, A_f. All the soft masses are taken to be at some unification scale, whose representative value adopted here is 1 TeV. When considering the light stop case we take a comparatively light value for $M_{U_3} \sim 250$ GeV, which corresponds to a stop mass of around 200 GeV, otherwise M_{U_3} is set to 1 TeV. In the Higgs scalar-pseudoscalar coupling the product of μA_f is relevant rather than μ or A_f separately. In our numerical analysis we have varied these parameters between 1 TeV and 2 TeV. M_{H^+} is varied between 100 and

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300 GeV. The mass of the lightest Higgs particle is then in the range of 100–130 GeV. As argued in our earlier works, the only phase that is relevant is the sum of the phases of μ and A_f. In our analysis we have kept $\phi_{A_f} = 0$ and studied the effect of CP violation by varying ϕ_μ. We analyse the cases with different $\tan\beta$ values in the following. Low $\tan\beta$ cases give very small deviations from the correponding CP-conserving cases, while large $\tan\beta$ cases produce significant differences. We take a representative value of $\tan\beta = 20$ to see the effect of the other parameters. In addition, to illustrate the cases of low and high $\tan\beta$ points, we present the analysis with $\tan\beta = 5$ and $\tan\beta = 50$ whilst keeping all other parameters constant.

In Fig.2 we plot the full cross section for $gg \rightarrow H_1 \rightarrow \gamma\gamma$ against M_{H^+}. We have considered $\mu = 1$ TeV, $A_f = 1$ TeV and $\tan\beta = 20$. There is appreciable variation of the cross section with ϕ_μ. Comparing the two cases of light and heavy stops, it is clear that the Higgs-stop-stop coupling is significant. Indeed, this was also noticed when we studied the di-photon decay [12].
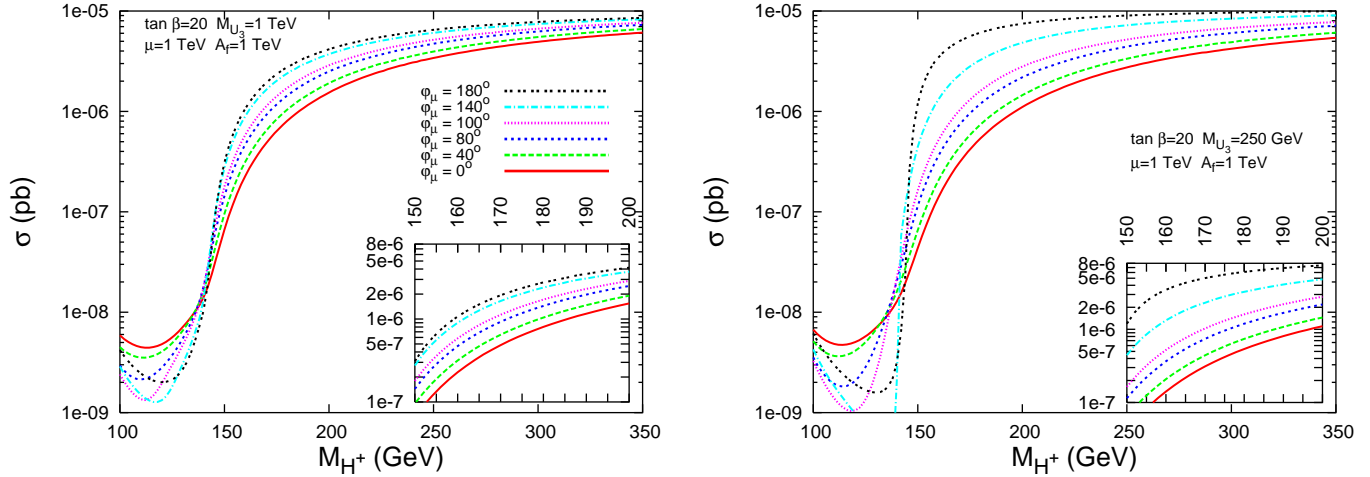

Figure 2: The cross section $\sigma(pp \rightarrow H_1 \rightarrow \gamma\gamma)$ at the LHC plotted against the charged Higgs mass for different ϕ_μ values. The relevant MSSM variables are set as follows: $\tan\beta = 20$, $A_f = 1$ TeV, $\mu = 1$ TeV, with $M_{U_3} = 1$ TeV (left plot) and $M_{U_3} = 250$ GeV (right plot).

Figs. 3 and 4 illustrate similar studies with $A_f = 1.5$ TeV, $\mu = 1$ TeV and $A_f = 1$ TeV, $\mu = 1.5$ TeV, respectively, in particular showing how significantly the result depends on A_f and μ. Unlike the case of Fig. 2, where there is only a quantitative difference between the two cases of light and heavy stop, in Fig. 3 we see that there is also a qualitative difference between the two cases (i.e., in the shape of the cross section curve). In contrast, Fig. 4 does only show a quantitative change, yet this simply has to do with the particular values of μ and A_f considered. In general, we may expect the difference between the CP-conserving and CP-violating cases to depend quite sensitively on A_f and μ.

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Figs. 5 and 6 show the cross section for $\tan\beta = 5$ and 50, respectively. In each case $A_f = 1$ TeV and $\mu = 1$ TeV are considered. As in the case of a di-photon decay considered independent of the production, here also cases with smaller $\tan\beta$ values are not very sensitive to CP-violating phases.

While in all the above cases a non-zero ϕ_μ was considered with vanishing ϕ_A, we have verified that the result is sensitive only to the combination $\phi_\mu + \phi_A$, and not to the individual phases. This is demonstrated in Fig. 7 by considering one case with $\phi_\mu = 0$, but varying ϕ_A. This situation may be compared with Fig. 2, where ϕ_μ is varied while keeping $\phi_A = 0$.
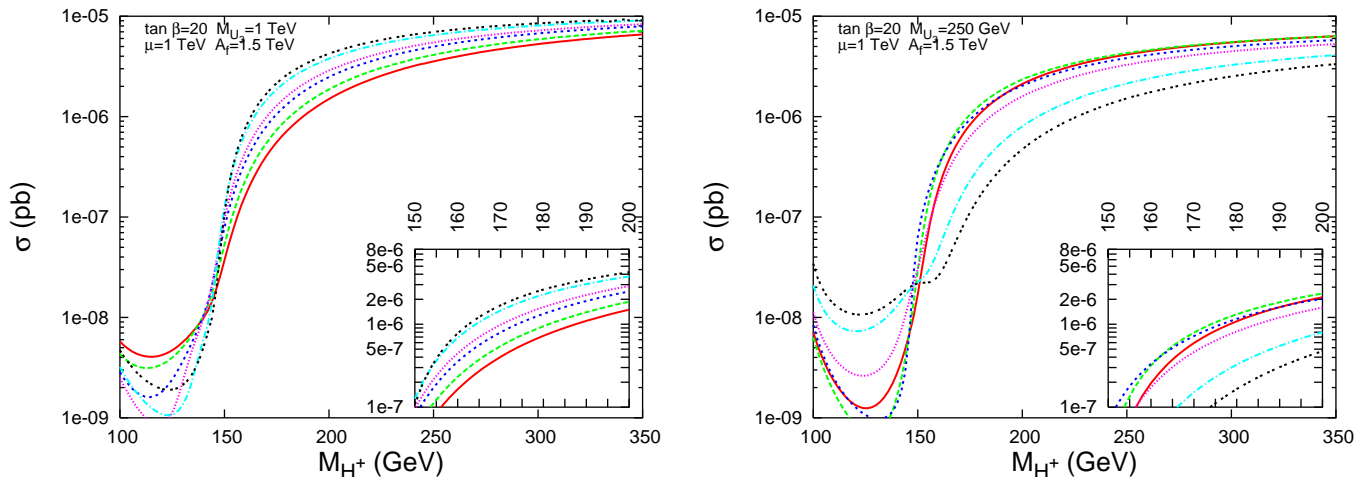

Figure 3: Same as Fig. 2, but with $A_f = 1.5$ TeV

In addition to the stop mass dependence of the $gg \to H_1 \to \gamma\gamma$ cross section, we have also studied how the latter varies with the masses of the other (s)particles entering the loops. However, in line with the results of Refs. [11]–[14] for the case of the $H_1 \to \gamma\gamma$ decay, we have found that their impact is largely negligible here too, no matter the value of the CP-violating phases. Nonetheless, one last aspect ought to be explored in connection with the $m_{\tilde{t}_1}$ dependence: how the value of the latter is itself affected by the CP-violating phases. In Fig. 8 we plot the variation of the lightest stop mass with the phase of μ for different parameter space points considered in the earlier plots. For example, if $\tan\beta = 20$, when $\mu = 1.5$ TeV and $A_f = 1$ TeV, the mass $m_{\tilde{t}_1}$ lies within $\sim \pm 2\%$ of its average value whereas, for $\mu = 1$ TeV and $A_f = 1.5$ TeV, it lies within $\sim \pm 5\%$ of it. For $\tan\beta = 50$ the spread is even narrower ($\sim \pm 1\%$) while for $\tan\beta = 5$ it is much larger ($\sim \pm 10\%$). Notice though that these variations are typically smaller than the experimental resolution expected at the LHC in measuring $m_{\tilde{t}_1}$. Therefore, an intriguing prospect appears, that the discovery of a light MSSM Higgs boson (with mass below 130 GeV or so) at the LHC may eventually enable one to disentangle the CP-violating case from the CP-conserving one, so long that the relevant SUSY parameters entering $gg \to H_1 \to \gamma\gamma$ are measured elsewhere, in particular $m_{\tilde{t}_1}$. This is not phenomenologically unconceivable, as this Higgs detection mode requires a very high
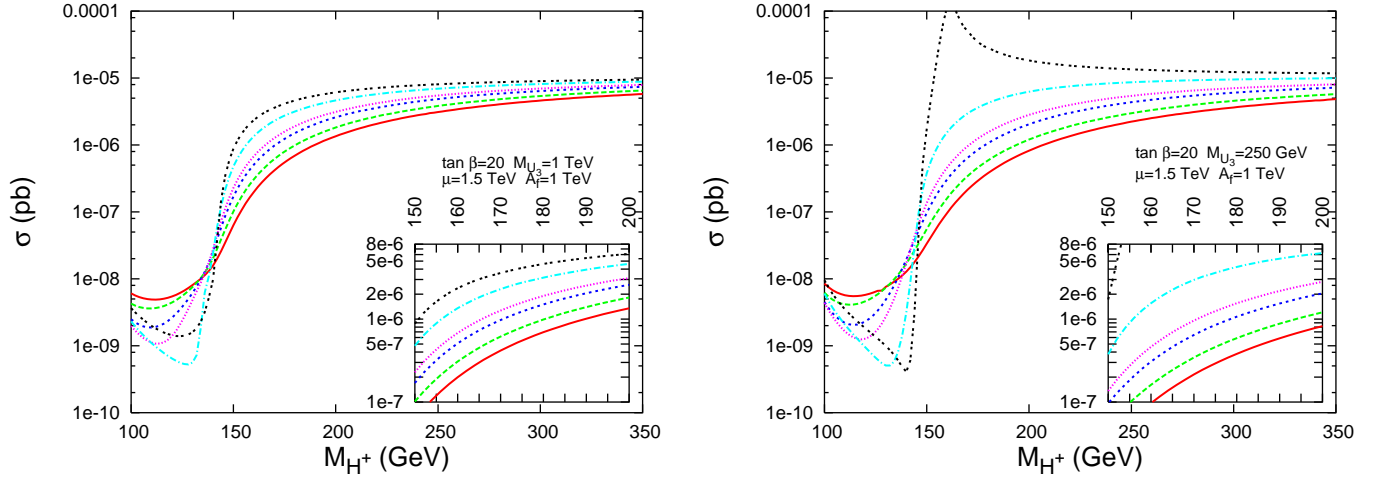
Figure 4: Same as Fig. 2, but with $\mu = 1.5$ TeV

luminosity, unlike the discovery of those sparticles (and the measurement of their masses and couplings) that enter the loops.

4   Conclusions

We have shown the conspicuous effects of CP violation onto the LHC cross section for $gg \rightarrow H_1 \rightarrow \gamma\gamma$ in the MSSM, as the overall production and decay rate varies over orders of magnitude, depending on the value of ϕ_μ (or, alternatively, ϕ_A). Varying the mass of the stop quark from 1 TeV or so to around 250 GeV has also a strong impact on the cross section, possibly changing its dependence on the phases qualitatively. Altogether then, it is clear that the prime detection channel of a light MSSM Higgs boson at the LHC is also a prime candidate to prove the existence of explicit CP violation in minimal SUSY.

5   Acknowledgement

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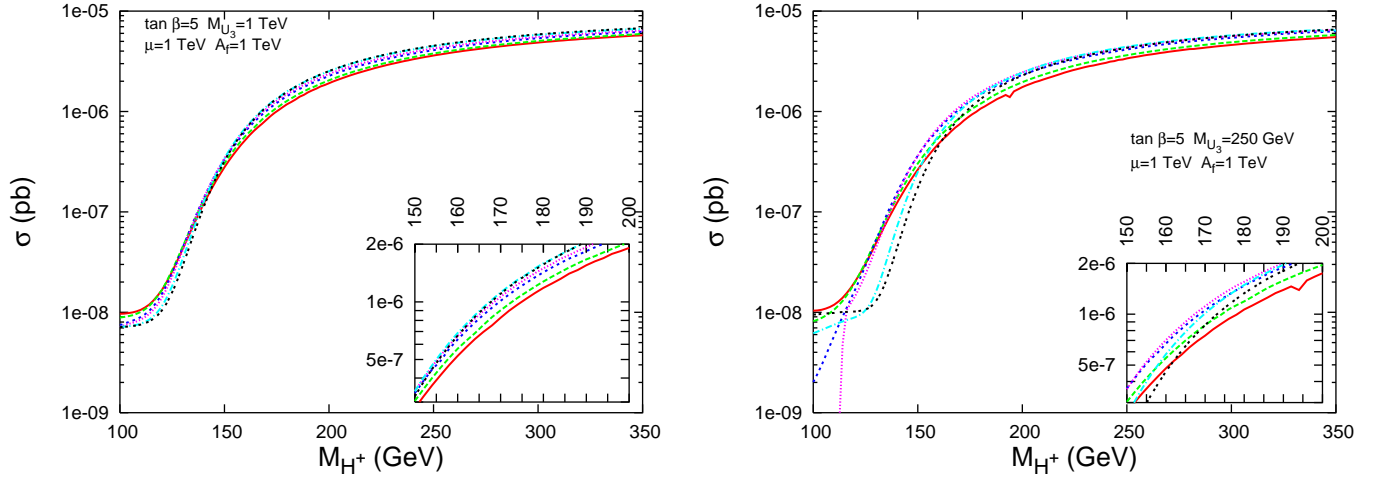
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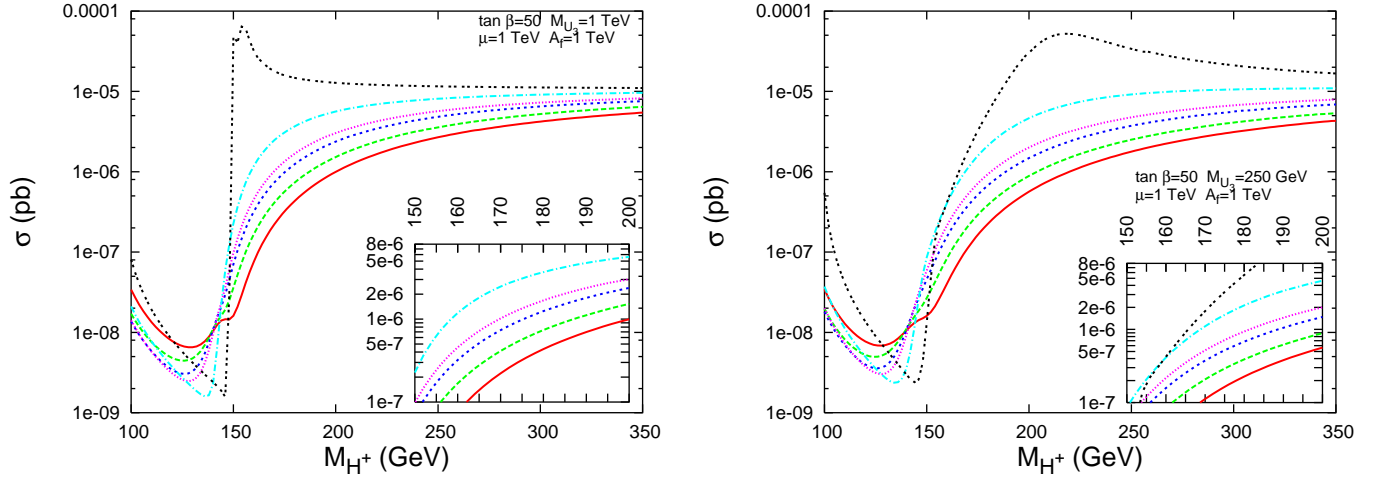[11] S. Hesselbach, S. Moretti, S. Munir, P. Poulose, arXiv:0710.4923 [hep-ph].

Figure 6: Same as Fig. 2, but with $\tan\beta = 50$.

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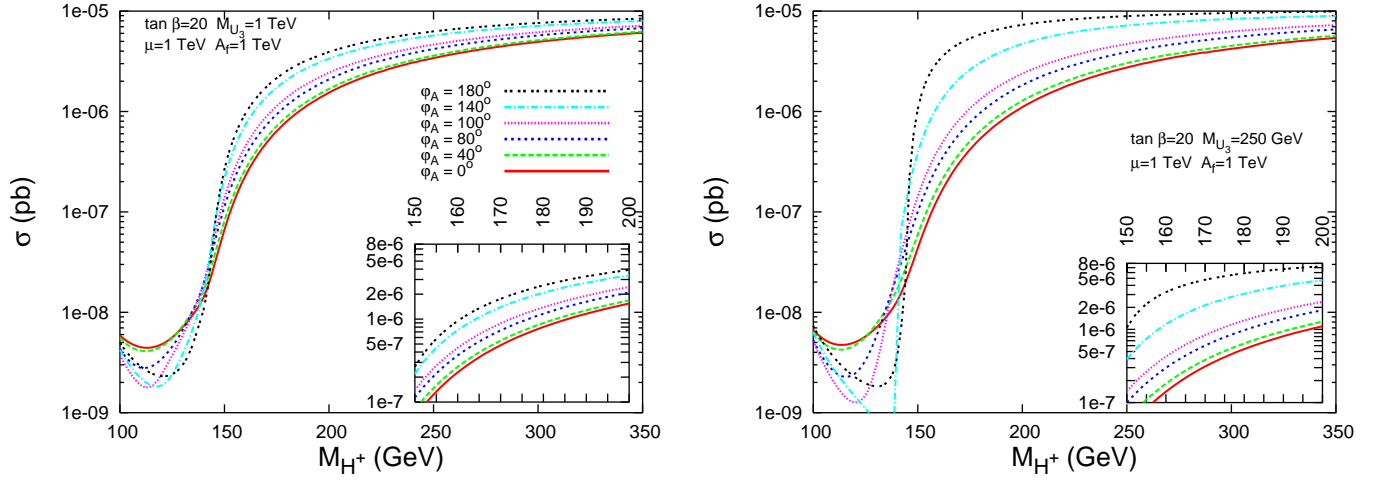[22] J. S. Lee, M. Carena, J. Ellis, A. Pilaftsis, C. E. M. Wagner, arXiv:**0712.2360v2** [hep-ph].

Figure 7: Cross section $\sigma(pp \to H_1 \to \gamma\gamma)$ at the LHC plotted against the charged Higgs mass for different ϕ_A values. Relevant MSSM variables are as follows: $\tan\beta = 20$, $A_f = 1$ TeV, $\mu = 1$ TeV, with $M_{U_3} = 1$ TeV (left plot) and $M_{U_3} = 250$ GeV (right plot).

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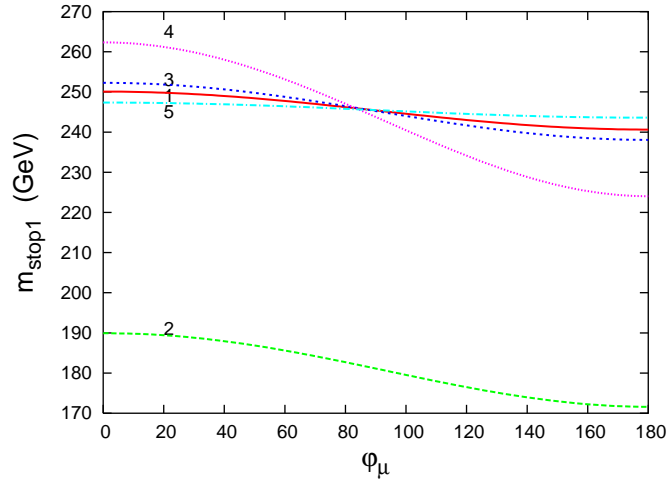
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Figure 8: Variation of $m_{\tilde{t}_1}$ with ϕ_μ. Case 1: $\tan\beta = 20$, $\mu = 1$ TeV, $A_f = 1$ TeV. Case 2: $\tan\beta = 20$, $\mu = 1$ TeV, $A_f = 1.5$ TeV. Case 3: $\tan\beta = 20$, $\mu = 1.5$ TeV, $A_f = 1$ TeV. Case 4: $\tan\beta = 5$, $\mu = 1$ TeV, $A_f = 1$ TeV. Case 5: $\tan\beta = 50$, $\mu = 1$ TeV, $A_f = 1$ TeV. In all cases $M_{U_3} = 250$ GeV.